

## IMPLICATIONS OF MORPHODYNAMIC TIME SCALE FOR COASTAL PROTECTION

HANS HANSON and MAGNUS LARSON

*Department of Water Resources Engineering, Lund University, Box 118,  
Lund, Sweden S-22100, Hans.Hanson@tvrl.lth.se, Magnus.Larson@tvrl.lth.se*

As reported in several studies, even though properly designed, it is possible that groin systems not only cause down-drift beaches to erode, but also contribute to the generation of rip currents. These rip currents run along the updrift side of the structure, moving sediment offshore where it may be, at least in part, lost from the system. It is well known that the directionality of the incident waves is a central factor for the shoreline response to groins. Until now, however, this directionality has been characterized only by the ratio of net transport rate  $Q_n$  to gross transport rate  $Q_g$ . In this study it is concluded that the phase lag between the forcing and the morphodynamic response is another key factor responsible for these offshore losses. Based upon this, a relaxation time for open-coast systems and a non-dimensional morphodynamic response factor for groin compartments are introduced as new design parameters for groin systems. These parameters provide an indication about the time it takes for the morphodynamic system to adjust to a change in the hydrodynamic forcing conditions.

### 1. Introduction

The use of groins for coastal protection has become somewhat tarnished over the years. Even though groins undoubtedly may maintain beach width, reduce losses from beach fills, prevent sediment transport into inlets and channels, etc., the world has seen many cases where groins have contributed to down-drift erosion. Clearly, our understanding of relevant design parameters needs to be enhanced to improve the functional design of these structures. The wave-induced longshore sediment transport rate depends on the angle between the breaking waves and the shoreline. By splitting the shoreline into shorter stretches by a groin or groin field, each compartment may be more easily reoriented by the incident breaking waves. Ideally, the shoreline will be reshaped to become locally parallel with the breaking wave crests, at which point the wave-induced longshore sediment transport rate approaches zero. At that time, an equilibrium plan shape will be reached (Figure 1a).

The situation remains stable until the incident waves arrive and break at a different angle (Figure 1b). If the change is significant, a considerable longshore current may be generated. At the location of the down-drift groin, the current is re-directed offshore in the form of a rip current. This is a well-known phenomena reported in several text books (see, e.g., Silvester and Hsu 1993). In

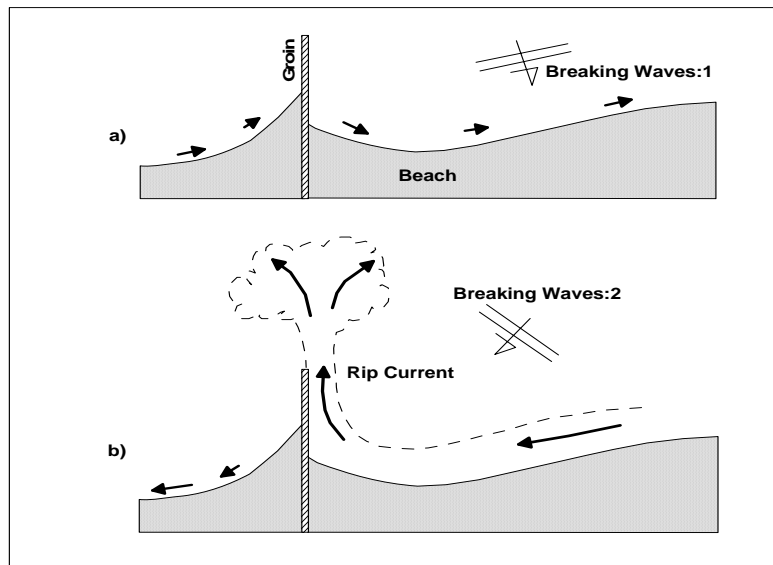


Figure 1. Schematic illustration of rip current development near a groin due to changing wave direction.

this rip current, sediment is transported offshore and may become, at least partly and locally, lost from the nearshore system. The plan shape gradually approaches a new equilibrium shape at which point the longshore as well the rip transport approaches zero.

This transition plays a central role for the functioning of the groin (system). Despite this, there are no design guidelines that take the variability of breaking wave direction into account. This paper discusses the impact of changing wave direction on shoreline evolution and associated offshore sediment losses through the application of analytic solutions as well the numerical shoreline change simulation model GENESIS. It is shown that 1) there is an inherent morphodynamic time scale associated with groin compartments, 2) the offshore losses are proportional to the offset between the forcing and the response, and 3) losses are at a minimum when changes in the forcing are of the same temporal scale as that of the response.

Shoreline change in the vicinity of disturbances that alter transport alongshore is controlled by the gross transport rate as well as the net (Bodge, 1992). Kraus *et al.* (1994) investigated the functioning of a single groin as a function the ratio of the net transport rate  $Q_n$  to the gross  $Q_g$ . The study showed that the impoundment on the updrift side increases with the ratio  $Q_n/Q_g$  while

holding  $Q_n$  fixed. In this study it will also be shown that, for the same ratio  $Q_n/Q_g$ , the offshore losses and the corresponding shoreline response are dependent on the frequency of the changing transport direction.

## 2. One-Line Modeling

The history and basic assumptions of one-line theory, with the line taken to represent the shoreline, are discussed extensively by Hanson and Kraus (1989). In the one-line model, longshore sand transport is assumed to occur uniformly over the beach profile down to a certain critical depth  $D$  called the depth of closure. By considering a control volume of sand and formulating a mass balance during an infinitesimal interval of time, while neglecting the cross-shore transport, the following differential equation is obtained,

$$\frac{\partial Q}{\partial x} + D \frac{\partial y}{\partial t} = 0 \quad (1)$$

where  $Q$  = longshore sediment (sand) transport rate,  $x$  = space coordinate along the axis parallel to the trend of the shoreline,  $y$  = the shoreline position, and  $t$  = time. Line discharges of sediment representing cross-shore transport can be added to Eq. (1) (Kraus and Harikai, 1983; Hanson and Kraus, 1989), but this capability is not exploited here.

Eq. (1) states that the longshore variation in the sand transport rate is balanced by changes in the shoreline position. In order to solve Eq. (1), it is necessary to specify an expression for the longshore sand transport rate. A general expression for this rate in agreement with several predictive formulations is,

$$Q = Q_o \sin 2\alpha_b \quad (2)$$

where  $Q_o$  = amplitude of longshore sand transport rate, and  $\alpha_b$  = angle between breaking wave crests and shoreline. This angle may be expressed as,

$$\alpha_b = \alpha_o - \arctan\left(\frac{\partial y}{\partial x}\right) \quad (3)$$

in which  $\alpha_o$  = angle of breaking wave crests relative to an axis set parallel to the trend of the shoreline, and  $\partial y/\partial x$  = local shoreline orientation

A wide range of expressions exists for the amplitude of the longshore sand transport rate, mainly based on empirical results. For example, the SPM (1984) gives the following equation,

$$Q_o = \frac{\rho}{16} H_b^2 C_{gb} \frac{K}{(\rho_s - \rho)(1 - \lambda)} \quad (4)$$

where  $\rho$  ( $\rho_s$ ) = density of water (sand),  $H_b$  = breaking wave height,  $C_{gb}$  = wave group velocity at the break point,  $K$  = non-dimensional empirical constant, and  $\lambda$  = porosity of sand. If Eq. (3) is substituted into Eq. (2), the sand transport rate can be written:

$$Q = Q_o \sin \left\{ 2 \left[ \alpha_o - \arctan \left( \frac{\partial y}{\partial x} \right) \right] \right\} \quad (5)$$

If solved numerically, these equations may be applied to describe a variety of situations and boundary conditions. To formulate an analytic solution, however, we are restricted to more simplified and schematized situations. As a first step towards an analytic approach, for beaches with mild slopes, it can safely be assumed that the breaking wave angle relative to the shoreline and the shoreline orientation, with respect to the chosen coordinate system, are small. The consequences and validity of this assumption that linearizes Eq. (5) are discussed further in Larson *et al.* (1987). Under the assumption of small angles, to first order in a Taylor series:

$$Q = Q_o \left( 2\alpha_o - 2 \frac{\partial y}{\partial x} \right) \quad (6)$$

If the amplitude of the longshore sand transport rate and the incident breaking wave angle are constant (independent of  $x$  and  $t$ ) the following equation may be derived from Eqs. (1) and (6),

$$\frac{\partial y}{\partial t} = \varepsilon \frac{\partial^2 y}{\partial x^2} \quad (7)$$

where,

$$\varepsilon = \frac{2Q_o}{D} \quad (8)$$

Eq. (7) is formally identical to the one-dimensional equation describing conduction of heat in solids or the diffusion equation and was first derived in the present context by Pelnard-Considère (1956). Thus, many analytical solutions can be generated by applying the proper analogies between initial and boundary conditions for shoreline evolution and the processes of heat conduction and diffusion. Carslaw and Jaeger (1959) provide many solutions to the heat conduction equation, and Crank (1975) gives solutions to the diffusion equation. The coefficient  $\varepsilon$ , having the dimensions of length squared over time, is interpreted as a diffusion coefficient expressing the time scale of shoreline change following a disturbance (due to wave action in the present case).

### 3. Analytic Solution of Shoreline Change in a Groin Compartment

For a groin compartment or for a beach enclosed by headlands, where no transport occurs across the boundaries, an analytical solution may be derived that displays some of the broad features of the response of a shoreline to seasonality in the wave climate (Dean 1983). The groins are represented by the boundary condition  $Q = 0$  at each groin location. Mathematically, this boundary condition can be expressed as (cf., Eq. 5):

$$\frac{\partial y}{\partial x} = \tan \alpha_o \quad (9)$$

This equation states that the shoreline at the respective groin is at every instant parallel to the breaking wave crests. In this case, the boundary condition in Eq. (9) should be employed both at  $x = 0$  and  $x = B$ , where  $B$  is the length of the groin compartment or enclosed beach. The breaking wave angle is assumed to vary according to the following expression,

$$\alpha_o(t) = \alpha_{ao} \sin \omega t \quad (10)$$

where  $\alpha_{ao}$  is the angle amplitude and  $\omega$  is the angular frequency of the wave direction. The solution at steady-state conditions may be written (c.f. Larson *et al.* 1997),

$$y(x,t) = \frac{\alpha_{ao} \sqrt{\varepsilon / \omega}}{2(\cosh \zeta + \cos \zeta)} \left[ e^{\zeta \frac{x}{B}} \sin \left( \omega t - \frac{\pi}{4} + \zeta \left( \frac{x}{B} - 1 \right) \right) + e^{\zeta \left( \frac{x}{B} - 1 \right)} \sin \left( \omega t - \frac{\pi}{4} + \zeta \frac{x}{B} \right) - e^{-\zeta \left( \frac{x}{B} - 1 \right)} \sin \left( \omega t - \frac{\pi}{4} - \zeta \frac{x}{B} \right) - e^{-\zeta \frac{x}{B}} \sin \left( \omega t - \frac{\pi}{4} - \zeta \left( \frac{x}{B} - 1 \right) \right) \right] \quad (11)$$

where:

$$\zeta = \sqrt{\frac{\omega B^2}{2\varepsilon}} \quad (12)$$

This non-dimensional parameter  $\zeta$  is called the *morphodynamic response factor* as it is an indicator of the response time of the shoreline to the variation in input wave conditions. As seen from Eq. (11), the (steady-state) solution is uniquely determined by the parameter  $\zeta$  for a fixed  $\alpha_{ao}$ ; that is, cases with the same  $\zeta$  will have identical dimensionless shoreline evolution ( $y/B$ ) expressed in  $x/B$  and  $t\varepsilon/B^2$ . Figures 2 and 3 display the solution (Eq. 11) at different phase values for  $\zeta = 1.0$  and  $\zeta = 6.0$ , respectively, where the dimensionless shoreline position was also normalized with  $\alpha_{ao}$ . A small value of  $\zeta$  implies rapid

response in shoreline orientation to the incident waves, and the shoreline lies almost parallel to the wave crests at all times (Fig. 2). The parameter  $\zeta$  becomes small if the amplitude of the transport rate  $Q_o$  is large, the length of the enclosed beach  $B$  small, or the frequency  $\omega$  of the wave angle variation small. For large  $\zeta$  there is a distinct phase difference between the shoreline response and  $\alpha_o$  (Fig. 3) and the oscillation in the shoreline position is less than for smaller  $\zeta$ . For very large  $\zeta$ , there will be no effect on the shoreline except close to the boundaries. The complete solution also has a transient part. However, this part decays exponentially with time and is not included in (11).

#### 4. Analytic Solution of Shoreline Change at a Single Groin including Offshore Losses in a Rip Current

As indicated by the previous case, situations with higher values on the morphodynamic response factor  $\zeta$  result in shorelines with larger curvature ( $\partial^2 y / dx^2$ ) near the groin. Thus, with the shoreline orientation closest to the groin corresponding to  $Q = 0$  as well as a zero wave-generated longshore current, a larger curvature indicates that the shoreline orientation a bit further away from the groin corresponds to a larger transport rate (and longshore current velocity) that, if directed towards the groin, is anticipated to generate an offshore rip-related transport. This also follows from Eq. (6) where  $Q$  is seen to be proportional to  $\partial y / \partial x$ , leading to  $\partial Q / \partial x \sim \partial^2 y / \partial x^2$ . In mathematical terms this boundary condition at the groin location is formulated as,

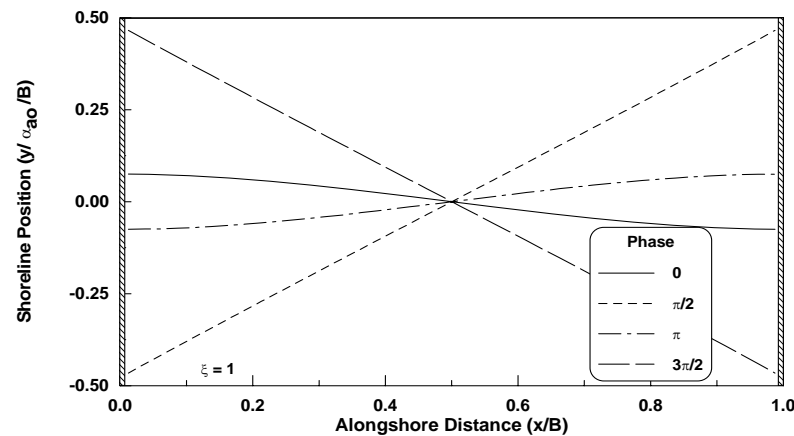


Figure 2. Shoreline evolution in enclosed groin compartment at steady-state conditions when breaking-wave angle varies sinusoidally with time for  $\zeta = 1$ . (Modified from Larson *et al.* 1997).

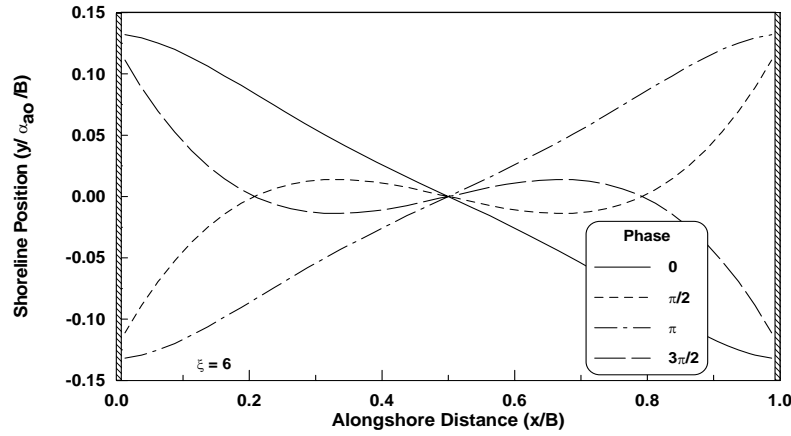


Figure 3. Shoreline evolution in enclosed groin compartment at steady-state conditions when breaking-wave angle varies sinusoidally with time for  $\zeta = 6$ .

$$Q_{off} = -R \left. \frac{\partial Q}{\partial x} \right|_{x=0} = 2RQ_o \left. \frac{\partial^2 y}{\partial x^2} \right|_{x=0} \quad (13)$$

where  $R$  is a dimensional coefficient [m]. If the wave crests make a constant angle  $-\alpha_0$  with the  $x$ -axis, giving rise to a longshore transport in the negative  $x$ -direction, the solution describing the accumulation on the updrift side becomes,

$$y(x,t) = -\alpha_0 \left[ 2\sqrt{\frac{\varepsilon t}{\pi}} e^{-\frac{x^2}{4\varepsilon t}} - (R+x) \operatorname{erfc}\left(\frac{x}{2\sqrt{\varepsilon t}}\right) + R e^{\frac{x}{R} + \frac{\varepsilon t}{R^2}} \operatorname{erfc}\left(\frac{x}{2\sqrt{\varepsilon t}} + \frac{\sqrt{\varepsilon t}}{R}\right) \right] \quad (14)$$

A non-dimensional plot of this shoreline evolution is shown in Figure 4 where the solution for  $R = 0.5$  (saying that half of the transport rate approaching the groin is redirected into the rip) is shown and compared to the case  $R = 0$ , i.e. no offshore rip transport. Based on Eq. (13), the offshore transport  $Q_{off}$  next to the groin becomes:

$$Q_{off} = 2RQ_o \left. \frac{\partial^2 y}{\partial x^2} \right|_{x=0} = -2RQ_o \alpha_0 \left[ \frac{1}{\sqrt{\pi \varepsilon t}} e^{-x^2/4\varepsilon t} + \right. \\ \left. + \frac{1}{R} e^{\left(\frac{x}{R} + \frac{\varepsilon t}{R^2}\right)} \operatorname{erfc}\left(\frac{x}{2\sqrt{\varepsilon t}} + \frac{\sqrt{\varepsilon t}}{R}\right) - \frac{1}{\sqrt{\pi \varepsilon t}} e^{-\left(\frac{x}{2\sqrt{\varepsilon t}} + \frac{\sqrt{\varepsilon t}}{R}\right)^2} \right] \quad (15)$$

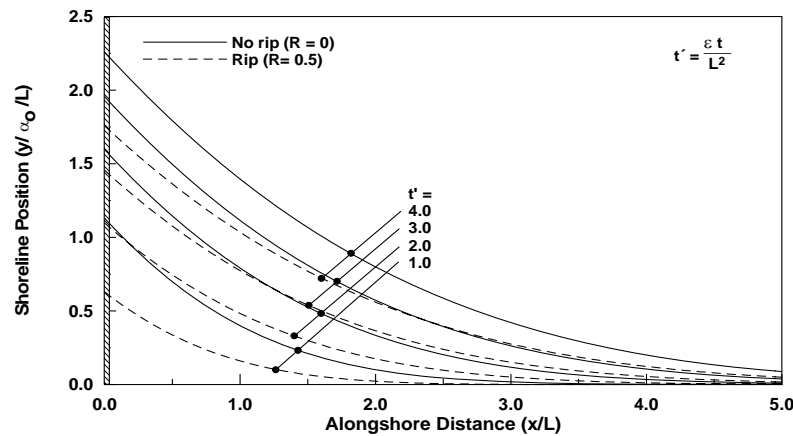


Figure 4. Shoreline evolution updrift of a groin with and without offshore loss in rip current ( $\alpha_o = 11.5$  deg).

Figure 5 shows that the relative offshore transport rate  $Q_{off}/Q_{off,init}$ , where  $Q_{off,init}$  is  $Q_{off}$  at  $t = 0$ , decreases to about 25% of the initial value after about a dimensionless time  $t' = 5.5$ , where  $t' = \varepsilon t/L^2$ , and  $L$  is a characteristic length, in this case preferably set to the groin length  $GL$ . This result is independent of  $Q_o$  and  $\alpha_o$ . Thus, to take benefit of the reduced offshore loss rates following shoreline reorientation, wave direction should not change more frequently than what corresponds to  $\varepsilon t/L^2 = 5.5$ , leading to  $t = 2.75 GL^2 D/Q_o$ . This time  $t$  may be regarded as a *relaxation time* for the system.

If this duration is used as an indicator, for example, with a longshore sand transport rate amplitude of  $500,000 \text{ m}^3/\text{yr}$ , a breaking wave angle of  $11.5$  deg, a groin length of  $100 \text{ m}$ , and a depth of closure of  $8 \text{ m}$ , the 'critical' wave direction duration is close to  $64$  days. Thus, if the higher waves come out of the same overall direction for a longer period than  $64$  days at this particular location, there is likely to be longer periods with less offshore losses. On the other hand, if the with typically changes direction more frequently than this, offshore losses will be higher.

##### 5. Numerical Solution of Shoreline Change in a Groin Compartment including Offshore Losses in Rip Current

Without offshore losses this case is identical to the analytic solution above for a groin compartment. With an offshore loss included, this case can be considered as a combination of the two analytic solutions above. However, to solve the

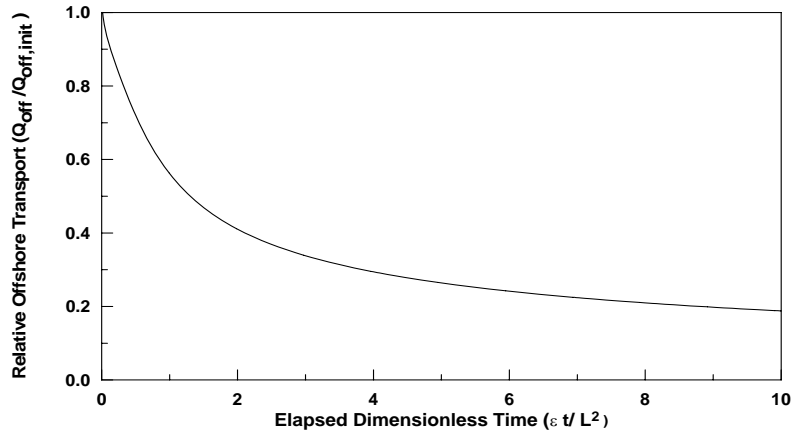


Figure 5. Relative offshore transport rate as a function of elapsed dimensionless time.

problem numerically the offshore rip loss is expressed in a slightly different way (formulated here for the loss  $Q_{off,L}$  at the left-hand lateral boundary),

$$Q_{off,L} = -R \left. \frac{\Delta Q}{\Delta x} \right|_{i=1} = -R \frac{Q_2 - Q_1}{\Delta x} = -R \frac{Q_2}{\Delta x} \quad (16)$$

where  $\Delta x$  is the alongshore grid spacing and  $Q_1$  is the transport across the lateral boundary. With an impermeable, long groin located here, the boundary condition is formulated  $Q_1 = 0$ . An equivalent boundary condition is formulated for the right-hand boundary. Figure 6 illustrates simulated interrelations between the offshore losses at each of the two groins (where  $Q_{off,R}$  is the loss at the right-hand lateral boundary) for a situation where the incident wave angle flips instantaneously between 11.5 and -11.5 deg every two months. The simulation starts out with a negative angle inducing an offshore rip current and associated offshore losses at the left-hand groin. The offshore transport rate starts out with a high value but decreases quite rapidly (in about two weeks) to a considerably lower value that remains fairly stable in time at around 5 m<sup>3</sup>/h. Simultaneously, the shoreline adjacent to the left-hand groin progrades towards the groin tip as it recedes at the right-hand groin. Because the initial shoreline was located at  $x = 0$ , the system is somewhat asymmetrical initially while at the end of the third cycles it seems like symmetry has been reached.

A series of simulations was then run to illustrate the impact of the *morphodynamic response factor*  $\zeta$  on the offshore rip losses following the above formulation of the lateral boundary conditions. In all cases, the wave angle varied sinusoidally according to Eq. (10) with  $1/\zeta$  set to 1, 2.25, 4, 9, and 36 days, respectively. With constant wave period  $T = 3$  sec, breaking wave height

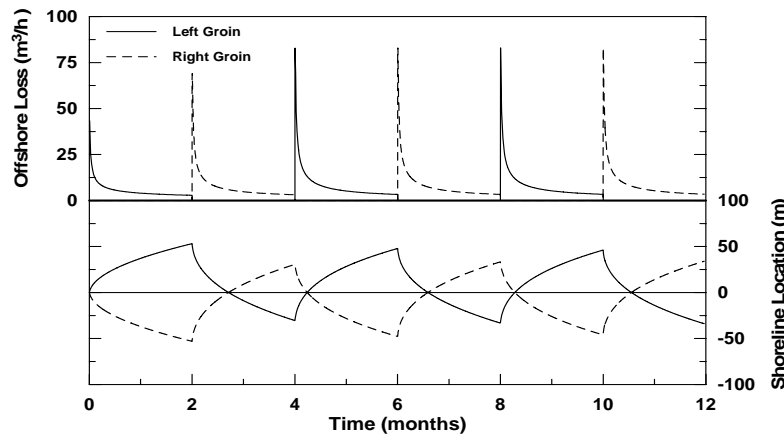


Figure 6. Simulated offshore losses and associated shoreline locations adjacent to lateral groins in a groin compartment with periodic, instantaneous change in wave direction.

$H = 0.87$  m, depth of closure  $D = 10$  m, and distance between groins  $B = 80$  m, the different  $\zeta$ -values corresponds to morphodynamic response factor  $\zeta$ -values of 6, 4, 3, 2, and 1, respectively. The higher values correspond to a situation where the variation in the hydrodynamic forcing is significantly faster than that of the morphodynamic response whereas the smaller values correspond to situations where the forcing and the response are more in phase. Thus, with smaller values, we would expect smaller offshore losses due to a structure-induced rip current. All simulations were run for a (prototype) duration of 252 days with  $R$  set to 0.5. The value of  $R$  is arbitrary as the analysis focuses on relative losses as a function of the *morphodynamic response factor*  $\zeta$ .

Figure 7 shows that for the slower change in wave direction ( $\zeta = 1$ ), the offshore loss of sediment was determined to about 10 per cent of the gross longshore transport rate  $Q_g$  half-way between the groins. With a more rapid change in wave directionality the relative losses are fairly stable up to about  $\zeta = 4$  from where the relative losses increase more quickly. However, in *absolute* terms ( $\text{m}^3 \cdot 10^3$ ) there is an almost linear increase of offshore losses with  $\zeta$ . Although this is a specific example setting it highlights the importance of keeping the value on the *morphodynamic response factor*  $\zeta$  down to reduce offshore losses.

Figure 8 illustrates the shoreline response in an enclosed groin compartment at steady-state conditions with no offshore losses (c.f. Fig. 2) and a similar situation with offshore losses corresponding to  $R = 0.5$  when breaking-wave angle varies sinusoidally with time for  $\zeta = 1$ . The shape of the shoreline seems to be independent of  $R$ , whereas its location is gradually receding as a result of

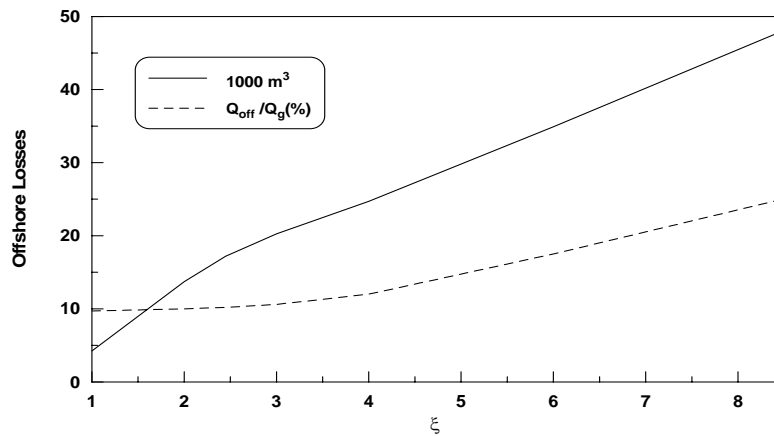


Figure 7. Offshore transport losses, expressed in  $10^3 \text{ m}^3$  and in percentage of the gross longshore transport rate  $Q_g$  half-way between the groins, in a groin compartment as a function of the morphodynamic response factor  $\zeta$ .

the offshore losses. Thus, as the shoreline orientation is preserved over time, the offshore loss through rip currents per wave cycle will not decrease with time. It should be noted, however, that diffraction from the groin tips is not considered in these simulations. If it were considered, there would probably be a gradual reduction in loss rate as erosion continues and the distance between the shoreline and the outer groin tips increase.

## 6. Concluding Discussion

The present study is based on the observation that rip currents are typically induced in the vicinity of groins and jetties in situations where there is a large difference in orientation between the shoreline and the breaking waves. Analytic and numerical solutions were applied to illustrate and quantify this phenomenon.

Previous studies have shown that not only the net longshore transport rate but also the gross rate is important for the shoreline response to groins and jetties. These rates and their relation are primarily associated with variability of wave directionality. The present study takes this discussion further in introducing the time scale or frequency of these changes. The difference in orientation between the hydrodynamic forcing (breaking waves) and the morphodynamic response (shoreline) may be interpreted as a phase shift between two systems that may have drastically different temporal scales.

For an open-coast system with a single groin or jetty exposed to an instantaneous change in the direction of the forcing, the critical time scale is

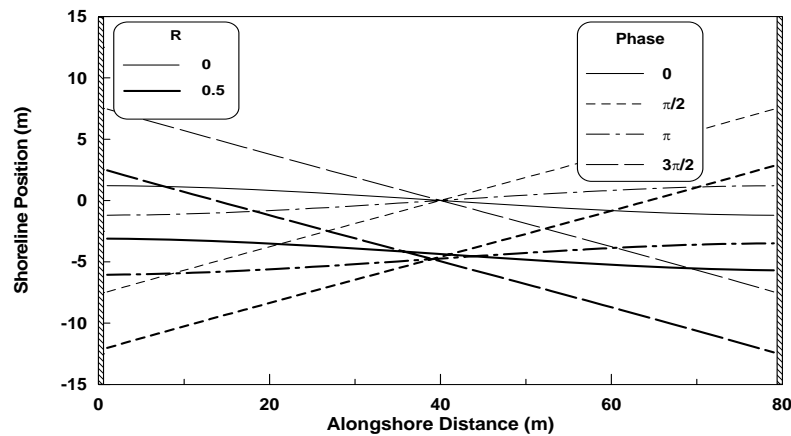


Figure 8. Comparison of shoreline evolution in enclosed groin compartment at steady-state conditions with no offshore losses ( $R = 0$ ) and a similar situation with offshore losses corresponding to  $R = 0.5$  when breaking-wave angle varies sinusoidally with time for  $\zeta = 1$ .

expressed in terms of a *relaxation time*. The value of this is site-specific but may be easily quantified from local conditions. By assuming that the offshore loss of sediment in these structure-induced rip currents is proportional to the transport gradient near the structure, the examples showed that the offshore losses of sediment are proportional to the phase shift between forcing and response. Thus, if the time between large changes in forcing (wave) direction is considerably shorter than the relaxation time, offshore sediment losses due to structure-induced rip currents may be significant.

In a groin compartment the relation between the two time scales is expressed by the *morphodynamic response factor*. As the value of this factor approaches 1, the variation in the forcing is slow enough for the response to keep even pace. As a result, offshore losses are kept at a minimum. When the  $\zeta$ -value increases, the phase shift between forcing and response also increases as do the offshore losses of sediment.

In summary, groins and jetties might best be considered for coastal protection in situations where offshore losses of sediment may be kept at a minimum. For this reason, the temporal behavior of wave directionality must be known. Based on this, a *relaxation time* for an open-coast single-groin system and a *morphodynamic response factor* for a groin compartment must be determined as they control the offshore losses from the system. If changes in wave direction are infrequent enough, offshore losses from structure-induced rip currents will be small, increasing the possibility that a groin (system) could function successfully.

### Acknowledgments

This paper was prepared as an activity of the Inlet Channels and Adjacent Shorelines Work Unit of the Coastal Inlets Research Program, U.S. Army Corps of Engineers (USACE) and partly funded through the U.S. Army Research, Development and Standardization Group, U.K. under Contract No. N68171-01-C-9017. Permission was granted by Headquarters, USACE, to publish this information. We appreciate reviews by Dr. Nicholas C. Kraus and others.

### References

- Bodge, K.R. 1992. Gross Transport Effects at Inlets. *Proc. 6<sup>th</sup> Annual National Conf. on Beach Preservation Technology*, Florida Shore & Beach Pres. Assoc., 112-127.
- Dean, R.G. 1983. *CRC Handbook of Coastal Processes and Erosion*, P.D. Komar, ed. CRC Press, Inc., Boca Raton, Fla.
- Carlsaw, H., and Jaeger, J. 1959. *Conduction of Heat in Solids*, Clarendon Press, Oxford.
- Crank, J. 1975. *The Mathematics of Diffusion*, 2<sup>nd</sup> ed., Clarendon Press, Oxford.
- Hanson, H. and Kraus, N.C. 1989. "GENESIS - Generalized Model for Simulating Shoreline Change," Vol. 1. Technical Reference, *Tech. Rep. CERC-89-19*, U.S. Army Engineer Waterways Experiment Station, Coastal Engineering Research Center, Vicksburg, MS.
- Kraus, N.C., Hanson, H., and Blomgren, S. 1994. Modern Functional Design of Groin Systems, *Proc. 24<sup>th</sup> Coastal Eng. Conf.*, ASCE, 1327-1342.
- Kraus, N.C. and Harikai, S. 1983. "Numerical Model of the Shoreline Change at Oarai Beach," *Coastal Engineering*, 7 (1): 1-28.
- Larson, M., Hanson, H., and Kraus, N. C. 1987. "Analytical Solutions of the One-Line Model of Shoreline Change," *Tech. Rep. CERC-87-15*, US Army Eng. Wtrwy. Exp. Sta., Coast. Engrg. Res. Ctr.
- Larson, M., Hanson, H., and Kraus, N. C., 1997. "Analytical Solutions of the One-Line Model for Shoreline Change near Coastal Structures," *J. Waterway, Port, Coastal and Ocean Eng.*, 123 (4): 180-191.
- Pelnaud-Considere, R. 1956. "Essai de Theorie de l'Evolution des Forms de Rivage en Plage de Sable et de Galets," *4<sup>th</sup> Journee de L'Hydraulique*, Les Energies de la Mer, Question III, Rapport No. 1, 289-298.
- Silvester, R. and Hsu, J.R.C. 1993. *Coastal Stabilization: Innovative Concepts*, Prentice Hall, Inc., New Jersey. ISBN 0-13-140310-9.
- SPM (Shore Protection Manual). 1984. 4<sup>th</sup> ed., 2 vols., US Army Engineer Waterways Experiment Station., Coastal Engineering Research Center., US Government Printing Office, Washington, DC.